NOISE PROPAGATION FROM VIBRATING STRUCTURES

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Abstract

Noise and noise exposure are becoming more important in product development due to environmental legislation. The reason for noise are vibrations of parts and assemblies during operation. Therefore, product development needs tools to judge the radiated noise of a product as soon as possible in the development cycle. A structural dynamics analysis using the Finite Element Method (FE) is such a standard tool, which provides useful information about the operational vibrations of products.

So, it is a natural extension of structural dynamics to use the vibration results of the structure to derive the radiated noise directly. Many methods to do this acoustic radiation analysis are available on the market either with Boundary Element Method (BEM), with Finite Element Method (FEM), or with other methods, but such tools are usually not integrated in structural dynamics. Such integration is highly desirable in order to unify and accelerate the calculation, because acoustic radiation analysis is known as rather time consuming.

The following sections will present the process to connect structural dynamics results with acoustic radiation of a part or assembly by using the commercial software PERMAS with the graphical user interface VisPER. The acoustic radiation analysis is also based on finite elements, which facilitates the integration with structural dynamics. Two examples will illustrate the process, a combustion engine and a transmission housing. Beside the process steps, the run time of acoustic analysis using High Performance Computing (HPC) devices is considered. Results will be shown which allow the evaluation and comparison of different structural designs.

1. Analysis Methods

Fig. 1 shows an overview on the process chain for acoustic radiation analysis using a combustion engine example (as also used in Helfrich et al. 2013). The first analysis is a modal frequency response analysis of the structure only. For the acoustic radiation analysis a direct frequency response is performed. So, we remain in the frequency domain for both structural dynamics and acoustic radiation analysis.

Doing both steps separately has the advantage that the structural dynamic analysis can be performed independently from any acoustic problem. Nevertheless, an acoustic analysis can be made for certain variants later.

Alternatively, a coupled analysis is also possible, which solves the frequency response analysis for both structure and surrounding fluid in a strongly coupled way (see Helfrich 2013). This coupled analysis provides both the structural response and the acoustic radiation at the same time. Because the coupled analysis is not needed for all structural dynamic problems, the separate solution of acoustic radiation is seen as a useful extension.

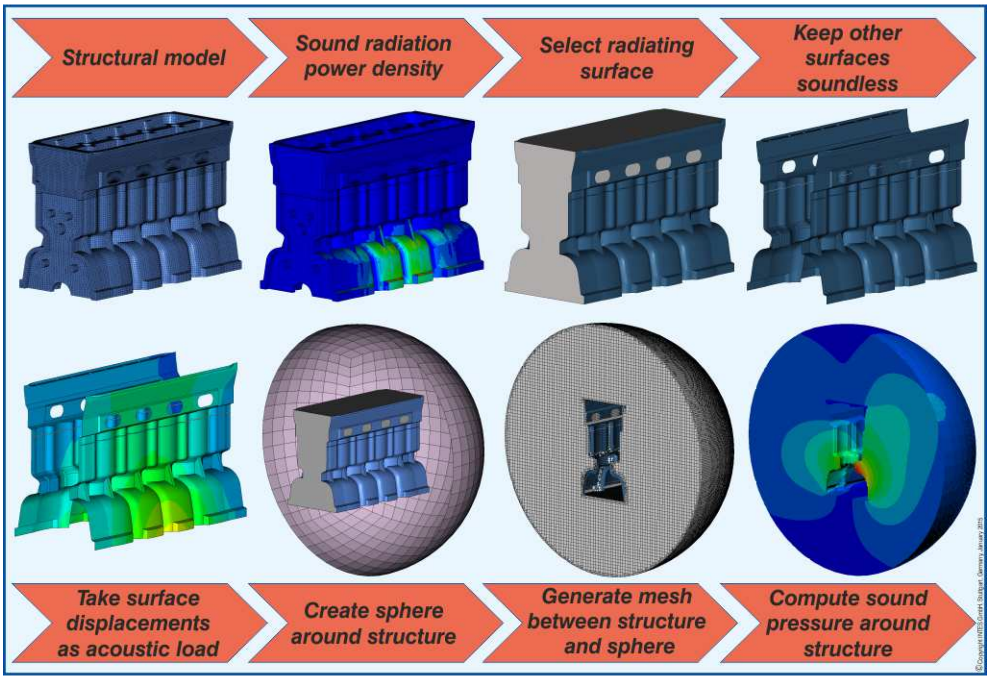

Figure 1: Process chain of acoustic radiation analysis.

2. Process of Acoustic Analysis

A frequency response analysis of the structure provides an acoustic relevant result, i.e. the sound radiation power, which is also available as sound radiation power density. The quantity is proportional to the square of the normal velocity at the surface either with the absolute value or as area specific value (denoted as density). The absolute values can be summed up in order to produce the complete sound radiation power of the radiating surface. Fig. 2 shows the frequency response curve of the sound radiation power at the side faces of the engine. Although the sound radiation power gives an indication of the most acoustically active surface parts, but it does not allow any prediction of the sound pressure in the surrounding fluid.

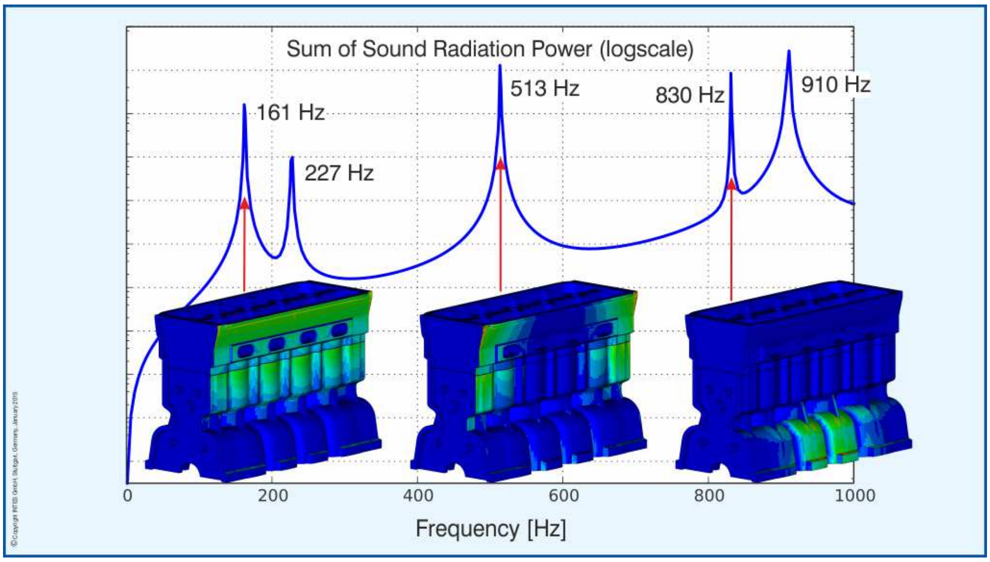

Figure 2: Structural frequency response of sound radiation power.

For the engine example the side faces are used as only surface parts, which are radiating noise to the surrounding.

The structural frequency response analysis was performed using a load where the valve seats are excited by forces with a phase shift between the cylinders. Displacements at the surface for all excitation frequencies are one primary result from the structural frequency response analysis. This result has to be extracted and prepared as acoustic load for the subsequent acoustic radiation analysis. It is worth mentioning that the calculated frequencies of the structural analysis determine the excitation frequencies in the subsequent acoustic radiation analysis. The latter can be used with less excitation frequencies, but there is no way to add more excitation frequencies without a previous structural dynamics calculation or by interpolation.

If no other structure is in the vicinity of the engine, then it is usual to take a sphere as outer boundary of the acoustic domain. The diameter of the sphere and the mesh size depend on the frequency range to be considered and the related wave length. The lower bound of the frequency range determines the diameter of the sphere, i.e. the diameter should be at least half of the related wave length. The upper bound of the frequency range is used to determine the maximum mesh size, i.e. half of the related wave length is discretized by six elements. Therefore, for lower frequencies the diameter has to be larger than for higher frequencies. And for a wider frequency range the model size is larger. In case of comparison with experiments, the distance between structure and microphone has also to be taken into account. The mesh shown in Fig. 3 is capable to solve acoustic radiation problems between about 200 and 4000 Hz.

The surface of the engine as previously selected is used as inner side of the acoustic domain. The engine is replaced by its surface, where the actively radiating parts are represented by special 2D interface elements. These elements have both structural degrees of freedom and pressure degrees of freedom. The displacement degrees of freedom are prescribed by the previously calculated structural displacements and the pressure degrees of freedom are the unknowns of the acoustic radiation analysis.

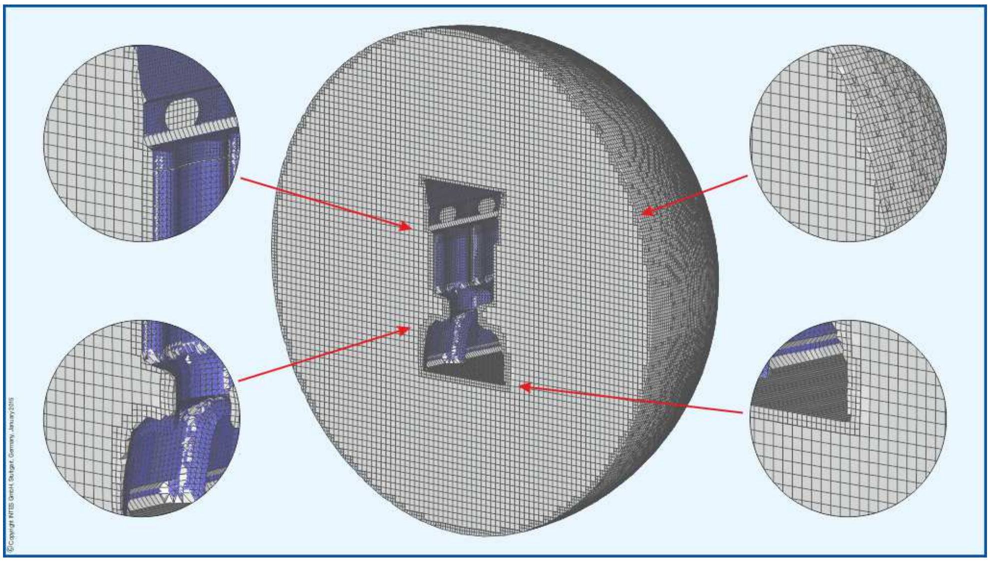

Figure 3: Automatically generated voxel mesh with mesh refinement.

The remaining step is the mesh generation between inner and outer boundary of the acoustic domain. This is done by an automatic voxel mesher, which is capable to refine the mesh near the surface as shown in Fig. 3. The elements used are hexahedra in the interior of the domain but also pentahedra, tetrahedra and pyramides at the boundaries. The advantage of the hexahedra-dominated fluid mesh is that the number of nodes and elements is much less compared to a tetrahedral mesh with the same mesh size. Near the boundaries a mesh refinement is made, which uses kinematically compatible interpolation approaches.

Waves in the acoustic domain, which are reaching the outer boundary of the acoustic domain, would be reflected. This is not the required boundary condition for radiation analysis. Therefore, so-called radiation boundary condition elements are applied at the outer boundary. For spherical shapes of the acoustic domain, elements following the theory of Bayliss and Turkel are used (see Bayliss et al. 1980).

Because the damping of air is rather low, the acoustic radiation analysis is often done without such damping. Here, we apply frequency-dependent volumetric drag, which ranges from about 0.3 Ns/m^4 at about 160 Hz to about 200 Ns/m^4 at 4000 Hz in a quadratic manner. These values were calculated, because no experimental results are available. Finally, after specifying the excitation frequencies, a direct frequency response analysis can be performed. The number of excitation frequencies is 311. The primary results are the pressure variations and the secondary results are the sound particle velocities. Fig. 4 shows a certain transfer function between two given nodes and the pressure level distribution in two cutting planes at 830 Hz.

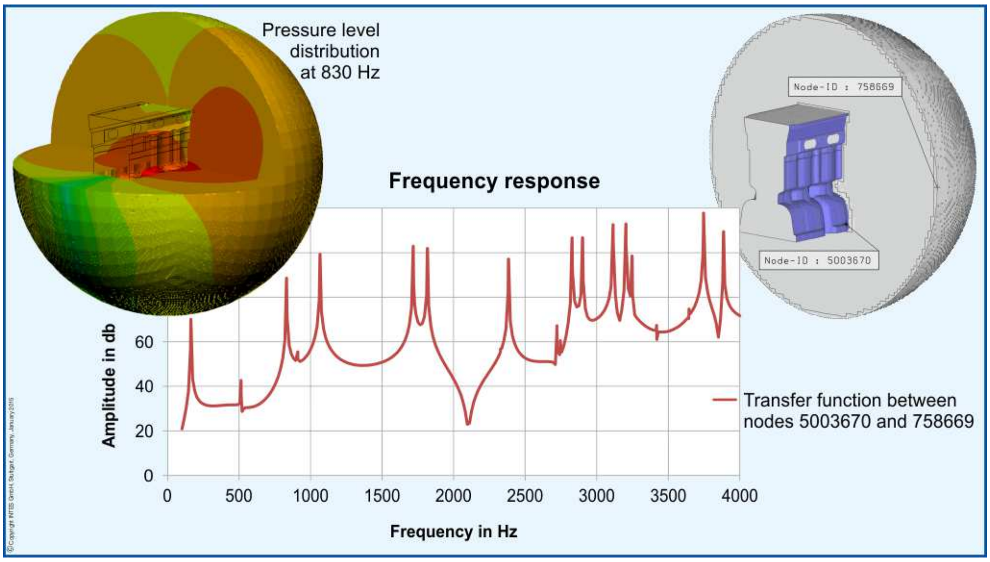

Figure 4: Acoustic transfer function and pressure level distribution.

If we correlate the frequency response functions of Fig. 2 to the transfer function in Fig. 4, then we can find the same peaks but with different amplitudes due to the different nature of the functions.

Fig. 5 shows the pressure level distribution over the diameter of the sphere along the X, Y and Z axes from the inner to the outer boundary at 830 Hz, which is one of the peaks in the excitation spectrum (see Fig. 2).

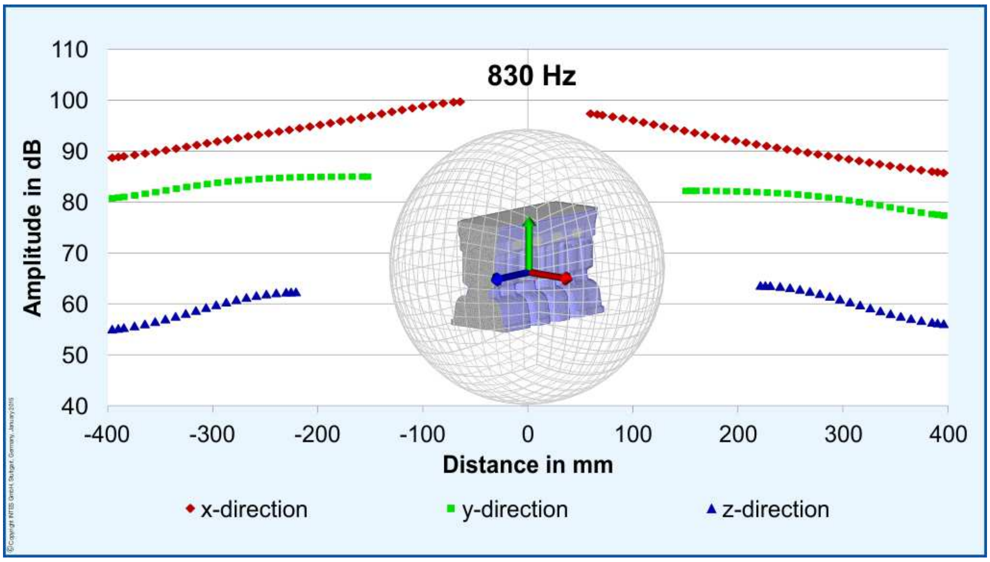

Figure 5: Pressure level distribution along the axes at 830 Hz.

3. Performance aspects

The engine model for acoustic radiation analysis has the characteristics as listed in Table 1. Additional MPC (Multi-Point Constraints) conditions are used between fluid mesh and inner and outer boundary as well as for the mesh refinement within the fluid domain.

Table 1: Characteristics of acoustic radiation model for engine.

No. of elements	Total	904,000
	Fluid	525,500
	Interface	51,000
	Radiation Boundary Condition	327,500
No. of nodes		744,500
No. of unknowns		439,500

Using a direct frequency response analysis, the run time will also depend on the number of excitation frequencies, where the run time is typically the same for all such frequencies.

The computer used is 1*14 cores Intel CPU E5-2697 with 2.6 GHz and 128 GB memory under Linux operating system. On this computer, the acoustic radiation analysis used about 1.5 minutes for each excitation frequency.

4. Complex Surfaces

While the previous engine example has a rather simple surface and only a part of the surface was radiating noise to demonstrate the process, the second example is from a complex transmission housing and the full surface is radiating noise. This model has already been investigated by test and simulation (see Neher 2012). The results are used as reference for the improved process described here. Here, the structural model is not known but the surface motion was given at 40 frequencies between 300 Hz and 4000 Hz. The overview on the process in this case is shown in Fig. 6.

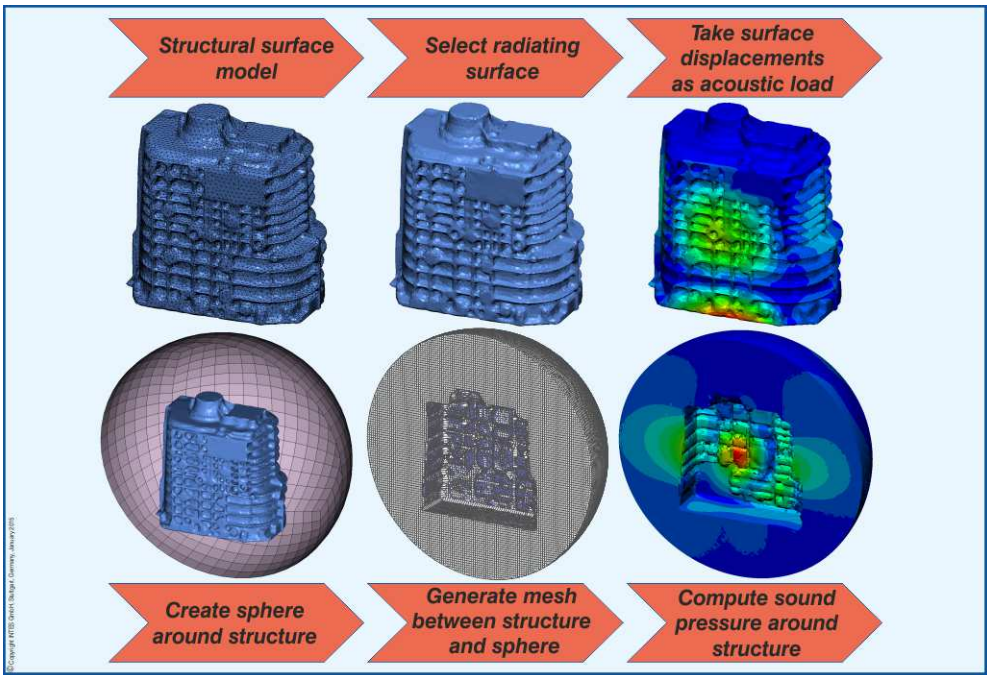

Figure 6: Process chain of acoustic radiation analysis for transmission housing.

The mesh is again generated by voxel meshing (see Fig. 7), where a mesh size of 8 mm has been used and a mesh refinement at the surfaces was not made due to the rather coarse mesh of both the inner and outer boundary of the acoustic domain.

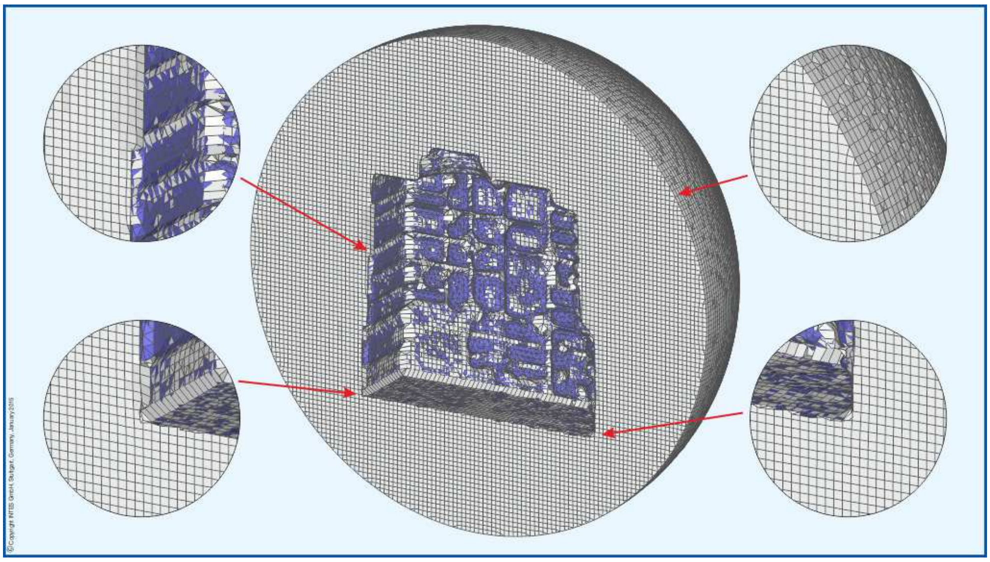

Figure 7: Automatically generated voxel mesh without refinement.

After specifying the excitation frequencies, a direct frequency response analysis can be performed. The number of excitation frequencies is 40.

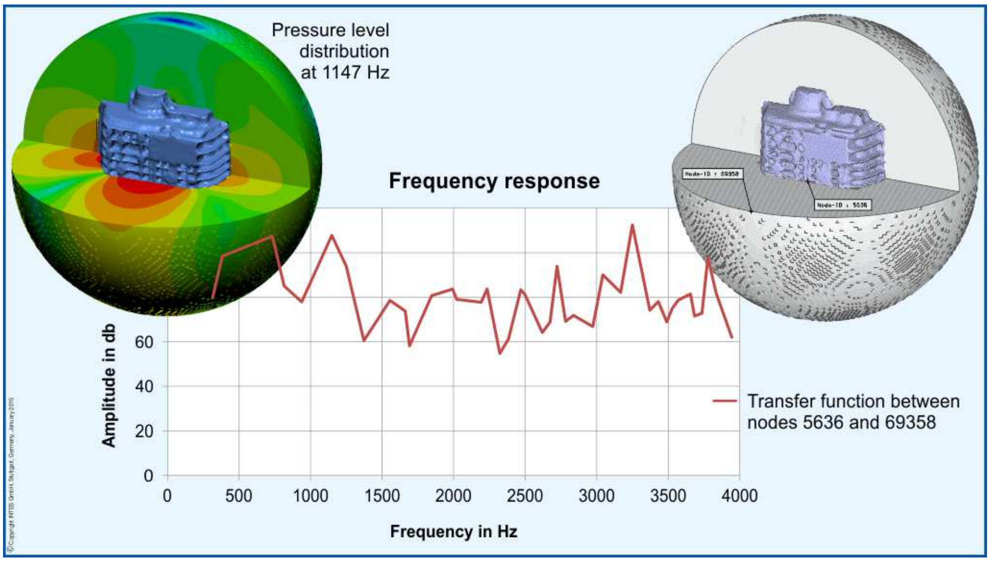

Figure 8: Acoustic transfer function and pressure level distribution.

The primary results are the pressure variations and the secondary results are the sound particle velocities. Fig. 8 shows a certain transfer function between two given nodes and the pressure level distribution in two cutting planes at 1147 Hz.

To compare the results with the literature (see Neher 2012), the pressure distribution at the surface of the structure is presented in Fig. 9 for three different frequencies.

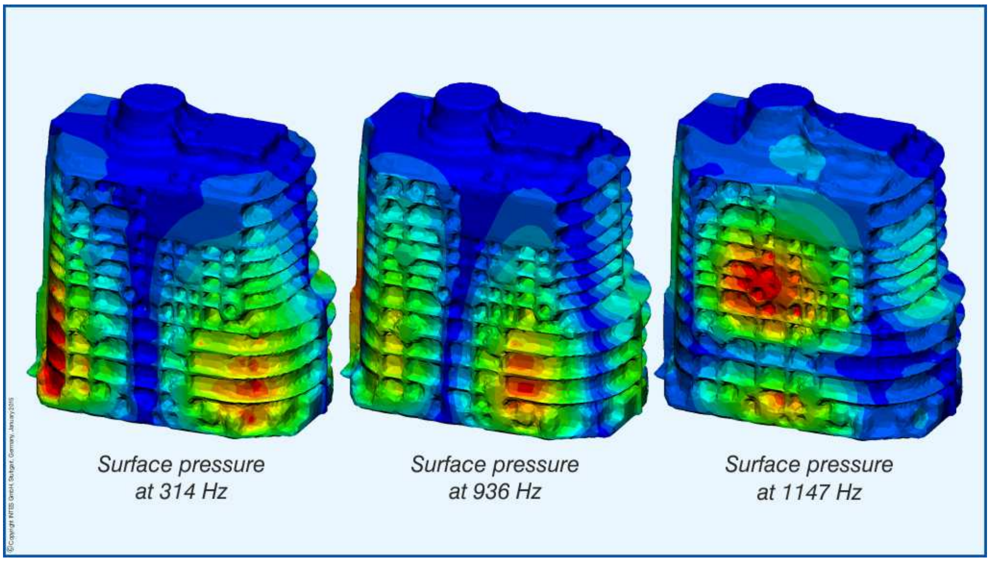

Figure 9: Resulting pressure distribution at structural surface.

The correlation with the literature is very good and shows very similar maximum pressures. The small differences might have the reason in a different mesh and slightly different damping values.

The transmission housing model for acoustic radiation analysis has the characteristics as listed in Table 2.

Table 2: Characteristics of acoustic model for transmission housing.

No. of elements	Total	747,702
	Fluid	637,084
	Interface	28,698
	Radiation Boundary Condition	81,920
No. of nodes		678,477
No. of unknowns		621,985

Additional MPC (Multi-Point Constraints) conditions are used between fluid mesh and inner and outer boundary as well as for the mesh refinement within the fluid domain.

The computer used is again 1*14 cores Intel CPU E5-2697 with 2.6 GHz and 128 GB memory under Linux operating system. On this computer, the acoustic radiation analysis used about 1.9 minutes for each excitation frequency.

5. Summary

The process of acoustic radiation analysis based on structural frequency response results has been shown using two examples, a combustion engine and a transmission housing. The process is implemented by Finite Elements in the commercial software PERMAS with the graphical user interface VisPER. For the surrounding mesh of the structure, a sphere is used with suitable radiation boundary conditions at the outer boundary. The meshes of the acoustic domain are generated by voxel meshes either with or without mesh refinement at the inner and outer boundary of the domain. The analysis method used is a direct frequency response analysis.

The run times for the models presented are rather short (in the low minute range) and depend nearly linearly on the number of excitation frequencies. The results of the transmission housing could be compared with verified results in literature and show a very good correspondence.

6. References

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